Power Switching Using Solid-State Relay

by T. C. McNulty

Solid-state relays make use of a semiconductor device for control of ac or dc power. Since, in most ac applications, the semiconductor element chosen for power control is the triac, this Note describes the triac as a power-switching element. Advantages and disadvantages of the active element over the electro-mechanical relay are discussed in general terms. Basic parameters, such as surge in-rush capability, transient-voltage ratings, suppression network, turn-off consideration and the different modes of triac gating are also discussed. AC power control is covered by various circuit designs for ON/OFF control, zero-voltage switching, and line-voltage isolation.

Power switching using electromechanical relays (EMR) is probably as old as the electrical industry is. The EMR is a controlled device having either an ON state or an OFF state capable of handling large amounts of power for a relatively low input power; it has widespread use in power and logic circuits. The relay comes in many forms (general purpose, telephone type, TO-5, reed, mercury wetted, etc.) and has various contact configurations. During the past few years, the EMR has been challenged by a new breed of relay which has no moving parts, is capable of handling large amounts of power for relatively low input power, and that comes in many package and circuit configurations. This new breed has been dubbed the "Solid-State Relay" or SSR, and uses transistors for dc power-control or triacs for ac power control. The SSR is particularly useful in areas in which increased reliability is required, and in which shock or mechanical fatigue impose severe limitations on the electromechanical relay. The major limitations to SSR use are economic factors, line isolation, immunity from line transients, and the need for multiple-pole arrangements.

TRIAC CONSTRUCTION

Thyristors (silicon controlled rectifiers and triacs) are semiconductor switches whose bistable state depends upon the regenerative feedback associated with a p-n-p-n structure. The SCR is a unidirectional device used primarily for dc and ac functions, whereas the triac is a bidirectional device used primarily for control of ac power.

The fabrication of a standard, glass-passivated triac requires the seven basic steps illustrated in Fig. 1 and delineated below.

1. The process begins with an n-type, high-resistivity, silicon wafer;
2. p layers are diffused deeply into both sides;
3. Silicon-dioxide diffusion masks are grown, and p+ regions are defined and diffused into the wafer;
4. A second oxide diffusion mask is grown, and n+ regions are defined and diffused into the wafer;
5. A silicon-dioxide etch mask is grown and defined. Grids and gate moats are etched into the wafer;

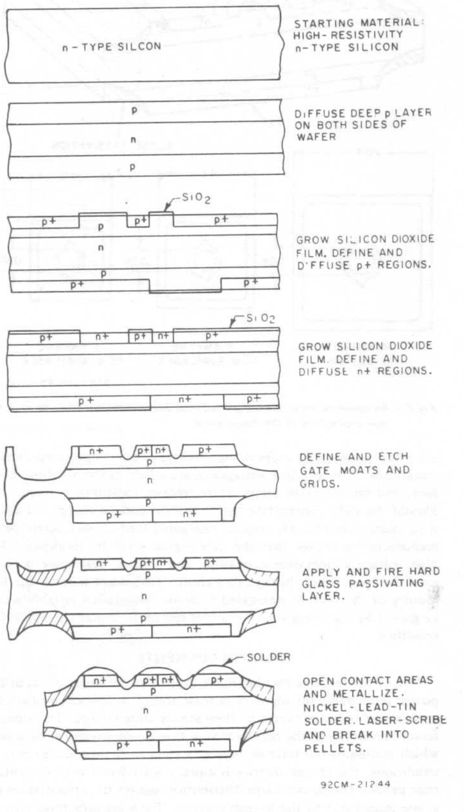

Fig.1 – The seven basic steps required in the fabrication of a standard, glass-passivated triac.

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6. A hard glass-passivated layer is applied in the grids and gate moat:

7. Contact areas are opened on the wafer and nickel-lead-tin solder metallization is applied. The wafer is then laser-scribed and separated into pellets. Fig. 2 contains an isometric view of a completed triac and dimensions of three devices now available or in the design stage.

VOLTAGE AND TEMPERATURE RATINGS

The effects of voltage and temperature are important in thyristors because of the regenerative action of these devices, and because they

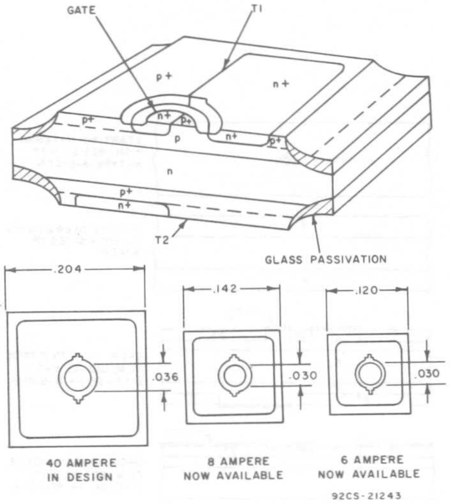

Fig.2 – An isometric view of a completed triac and dimensions of three devices now available or in the design stage.

are often required to support high voltages under high temperature conditions. The imposed voltages create a field at the junction interface, and the increased temperature releases additional surface ions. Should the field concentrate the additional surface charge and allow it to migrate into the gate region, non-gated turn-on may occur. Most manufacturers realize that the gate region must be terminated for high voltage/temperature operation, and a shunt resistance is built into the triac pellet during fabrication. This shunt reduces the immunity of the triac to non-gated turn-on. Additional reliability can be gained by operating the triac under less severe voltage/temperature conditions.

IN-RUSH CURRENTS

One of the features that has made thyristors the work-horses of the power semiconductor industry is their ability to absorb in-rush currents many times in excess of their steady-state ratings. This unique feature results from the regenerative action of the thyristor, an action which maintains the internal beta at a level such that, under in-rush conditions, the charge density is equally distributed over the entire triac pellet. The equal charge distribution assures the presentation of a low impedance to the in-rush current. Each manufacturer clearly rates device surge capability from single cycle to multiple cycles. Since this rating cannot be exceeded repeatedly, care should be exercised in the actual application to provide a sufficient safety margin between the published ratings and the actual circuit in-rush currents.

Another important parameter associated with a triac is its di/dt rating, a parameter most significant during turn-on. With the initiation of a gate signal, the active area closest to the gate region is, essentially, turned on, and, for a few microseconds, the instantaneous power dissipation is a function of the rate of rise of the on-state current. This power dissipation may cause localized heating and result in silicon-lattice destruction and triac degradation. The di/dt ratings are a function of triac geometry and pellet size, and ratings of 100 A/μs are easily achieved. In most circuit applications, stray or actual-load inductance is present, and for the condition of di/dt = E_{pk}/L, it is easily seen that a few microhenries of inductance are all that are required to limit circuit di/dt to within the maximum rating. When di/dt ratings are exceeded, it is usually because of the RC snubber network in parallel with the triac. In such networks, stray inductance is essentially zero, and the magnitude of discharge current is limited by the snubber resistance. The di/dt in the snubber is not affected by the inductance added to quell the di/dt caused by the stray or actual-load inductance; only careful selection of RC-snubber-network components will eliminate this second source of di/dt and minimize triac failures.

TRANSIENT VOLTAGES

It is well known that triacs are susceptible to non-gated turn-on and possible damage as a result of transient voltages. Transients are generally caused in a triac by the switching of inductive loads on adjacent lines or in proximity to the device. If the transient voltage generated exceeds the critical rate-of-rise of the off-state voltage (dv/dt) then a displacement current ($i = C \cdot dv/dt$) is generated which causes non-gated turn-on. Non-gated turn-on is not destructive if the energy transfer is within the maximum rating of the device; however, if the transient voltage does not exceed the off-state dv/dt rating, but does exceed the maximum voltage rating, then triac breakover occurs. Whether triac degradation occurs is dependent on whether the energy transfer is within the bulk silicon or the edge avalance.

Although the transient-voltage problem may seem critical, there are precautions that can be taken to minimize it. The use of RC snubbers in parallel with the triac can reduce the rate of imposed transients. This arrangement is most effective for fast rising, short-duration line disturbances. For critical applications, the use of a voltage-clipping device in addition to an RC snubber effectively suppresses both the rate of rise and magnitude of line-generated transients.

Another type of transient particularly prevalent in the area of inductive loads, and often overlooked, is the circuit-induced transient. Consider an inductive load in series with a triac and RC snubber network which also includes a switch for line-voltage interruption. With the triac in the off state, a leakage current flows which is a function of the characteristics of the load, the RC snubber network, and triac leakage. If the switch is momentarily opened when the triac is off, then a voltage transient ($E = L \cdot di/dt$) is generated which can exceed the voltage rating of the triac, cause non-gated turn-on and abrupt energy transfer; and may result in damage to the triac. Again, the proper selection of RC-network components and voltage-clipping device will suppress the circuit-induced transient to a level compatible with the voltage rating of the triac.

COMMUTATING dv/dt

The term "turn-off time" is not associated with triacs since triacs are bidirectional, and reverse voltage is nothing more than a forward voltage to one-half of the triac chip. A new term, "critical-rate-of-rise-of-commutation-voltage", is used with triacs. The term describes the ability of the triac to turn off as the current passes through zero, or commutates. One must remember that the triac is a current-dependent device: current is injected into the gate to turn the device on, and current must be removed or allowed to pass through zero for turn-off regardless of what the source-voltage polarity is. Commutating dv/dt is less critical with resistive loads and most important with inductive loads. Consider an inductive load in which the load current lags the source voltage by a phase angle θ. As pointed out,

triac commutation occurs at zero current, whereas the source voltage has some magnitude E. As the load current crosses the zero point, a small reverse current is established as a result of the charge in the n-type region. This charge, plus a displacement current ($i = C{\cdot}dv/dt$) resulting from the reapplied source voltage, can cause the triac to turn on in the absence of a proper gate signal. A minimum commutating dv/dt at rated current and at a specific operating case temperature should be defined in all triac applications; the circuit designer can use these specifications to choose an RC snubber network that will limit the reapplied dv/dt to within ratings. Loss of triac control as a result of commutating dv/dt does not degrade the characteristics of the triac. Proper RC snubber network selections for worst-case conditions of load power factor, current, and voltage are easily made by use of the charts shown in Fig.3.

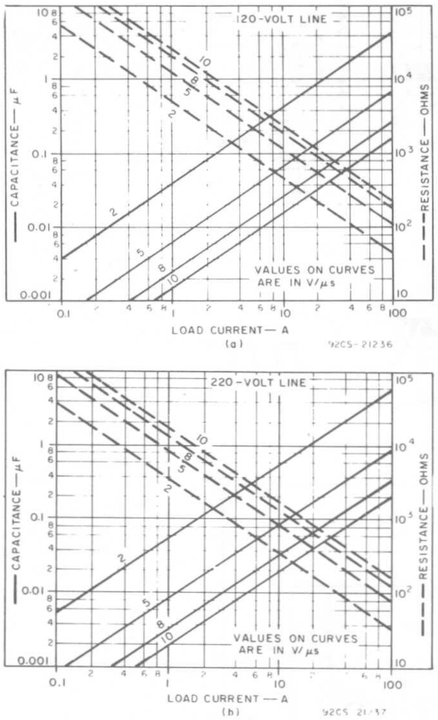

Fig.3 – (a) Snubber components for 200-volt peak on 120-volt line; (b) Snubber components for 400-volt peak on 220-volt line.

ADVANTAGES OF SSR's

Before the advantages of SSR's are discussed, the types available should be reviewed.

Two types of SSR are available: all solid-state and hybrids. The solid-state class employs solid-state devices for both logic and triac gating. Hybrids generally use a reed relay for triac gating for ac power control and so combine the electromechanical with solid state. In either class, the triac is used as the solid-state element for ac power control. A comparison of SSR's with electromechanical relays is given below.

Life: An EMR physically makes and breaks load current, and the relay contacts deteriorate with life.

SSR's: They have no moving parts, and may be designed to make and break at zero current. Regardless of the design, the triac always breaks at zero current.

Contact Bounce: Inherent with an EMR – zero for SSR's.

RFI: Inherent with EMR's – dependent on SSR design.

AFI: ("audio-frequency" interference). Terrible with EMR's, particularly when many relays are clacking about. Not noticeable with SSR's.

Environment: High humidity, corrosion, and explosive atmospheres usually dictates a sealed relay. SSR's may easily be potted.

Shock: The SSR is far superior.

Input Logic: EMR's can be operated from low-level logic. SSR's are design dependent, but offer complete versatility.

GENERAL CONTROL CIRCUITS

A simple triac control circuit, an ON/OFF circuit, is shown in Fig.4. With switch S1 open, the triac is off and essentially zero current is applied to the load. Actually, there will be leakage-current flow to the load; the amount of current is dependent on the applied voltage and triac case temperature. However, because the current is very small (less than one milliampere) compared to the load current, it can be neglected in this and the following circuits. (In specific applications in which leakage current may affect control it would have to be considered.)

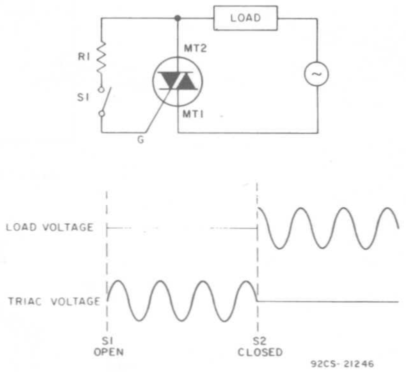

Fig.4 – ON/OFF control, non-synchronized.

To apply power to the load in Fig.4, switch S1 is closed to provide gate drive to the triac. Bias-resistor R1 is of the order of 68 to 100 ohms and provides the initial gate drive during every half cycle of applied voltage. The power consumption of R1 is very low (1/4 to 1/2 watt), because, when the triac is in the ON state, R1 is in parallel with the ON-state voltage of approximately 1.5 volts. This method of triac triggering, called anode firing, is an effective way of triggering because it uses the source voltage as a source of gate-current drive. Maximum gate current is available for triac turn-on at peak line voltage until the device goes to the low-impedance state. In this state the current in R1 is reduced by the forward voltage drop. In effect, bias resistor R1 is utilized only during the initial turn-on of the triac, or for approximately two microseconds. In a typical application, switch S1 would be replaced by a relay, and power control would be transferred by means of low-level-current relay contacts.

For control applications which require that variable power be delivered to a load, an inexpensive RC phase-control circuit is best. Fig.5 shows the basic triac-diac control circuit with the triac connected in series with the load. During the beginning of each half cycle

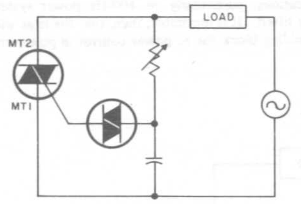

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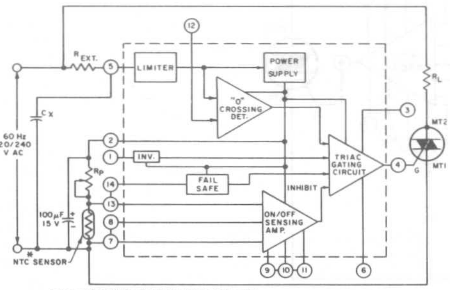
Fig.5 – RC phase control, variable power.

the triac is in the OFF state; as a result, the entire line voltage is impressed across it. Because the triac is in parallel with the potentiometer and capacitor, the voltage across the triac drives the current through the potentiometer and charges the capacitor. When the capacitor voltage reaches the breakover voltage of the diac, V_{BO}, the capacitor discharges through the triac gate and turns it on. The line voltage is then transferred from the triac to the load for the remainder of that half cycle. This sequence is repeated for every half cycle of either polarity. If the potentiometer resistance is reduced, the capacitor charges more rapidly, the V_{BO} of the diac is reached earlier in the cycle, and the power applied to the load is increased. If the potentiometer resistance is increased, triggering occurs later and load power is reduced. The main disadvantage of this circuit is that it produces RFI.

Although the basic light-control circuit operates with the component arrangement shown in Fig.5, additional components and sections are usually added to reduce hysteresis effects, extend the effective range of power control, and suppress radio-frequency interference.

TEMPERATURE-CONTROL CIRCUITS

A zero-voltage-switch, Fig.6, synchronized for line-pulse generation, in combination with a triac, is particularly well suited for temperature-control applications. The zero-voltage-switch/triac circuit



* NTC = NEGATIVE TEMPERATURE COEFFICIENT

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Fig.6 – Functional block diagram of the integrated-circuit zero-voltage-switch, CA3059.

may be used with an ON/OFF-type control or as a proportional control depending on the degree of regulation required. A simple, inexpensive, ON/OFF temperature controller is shown in Fig.7; a review of the functional block diagram of the zero-voltage-switch, Fig.6, will help in understanding the circuit. For every zero-voltage crossing, a zero crossing pulse is generated and directed to the triac gating circuit. If there is a demand for heat, the differential amplifier is in the open state, the triac gating circuit is open, and the triac is turned on at every zero-voltage crossing. When the demand for heat is satisfied, the differential amplifier is in the closed state; this inhibits the triac gating circuit and removes any further gate drive to the triac. Therefore, the key to the operation of this circuit is in the state of the differential amplifier. One side of the differential amplifier is biased to a reference voltage V_R, and the other side is biased to a voltage V_S which is dependent on a variable potentiometer setting and sensing resistor. As a result, whenever the bias voltage V_S exceeds the reference voltage V_R, the gating circuit is open and the triac is turned on for each zero-voltage crossing. The characteristics of an ON/OFF controller are well known; i.e., there are significant thermal overshoots and undershoots which result in a dif-

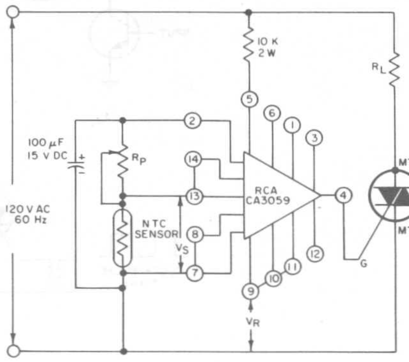

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Fig.7 – CA3059 ON/OFF temperature controller.

ferential temperature above and below the reference temperature. The magnitude of the differential temperature is dependent on the mass of the heater and the time constant of the sensing element.

For precise temperature control, the technique of proportional control with synchronous switching is introduced. The proportional control differs from the ON/OFF control in that it allows a specified percentage of power (duty cycle) to be supplied to the load with a finite off time that, in turn, allows the heating element to "catch up" as a result of thermal lag. In effect, this scheme provides "anticipator control." Again, the key to circuit operation is in the state of the differential amplifier.

AC LINE ISOLATION

The design engineer often must provide dc-to-ac isolation. Complete isolation can be achieved by reed relays, pulse transformers, and light-activated devices. Selection of any one of these three approaches depends on the dc logic design and component economics. Fig.8 (a) shows a reed relay and transistor drive circuit which is effective in triac gating, although it does have moving parts. Fig.8 (b) uses a pulse transformer for isolation, and requires a form of clock pulse that can be transferred to the triac gate. In some applications, clock pulses may already be available; therefore the pulse-transformer approach is economical. This approach requires more components than that of Fig.8 (a), but it has no moving parts. The last approach,

and, at present, probably the most expensive one, uses a light-activated device, such as the GaAs infrared (IR) emitter, to initiate triac gating. The light-activated device is coupled to a photosensitive transistor which, when turned on, provides inhibit logic for additional integrated circuits or, as in Fig. 8 (c), for a zero-voltage-switch application.

CONCLUSION

This paper has illuminated some of those areas most misunderstood or considered as problem areas in the application of triacs. The designer who thoroughly understands the characteristics and limitations, but most of all the advantages, of triacs, will have at his disposal a device that he can use to design power controllers that operate satisfactorily not only in normal applications, but also in severe physical and electrical environments. The triac has already proven to be a true power-semiconductor device, and is widely used in both commercial and industrial applications; restrictions on triac use in military applications, particularly in 400-Hz power systems, are gradually being lifted. It is inevitable, then, that the triac will evolve as the basic building block for ac power control in power-controller systems.

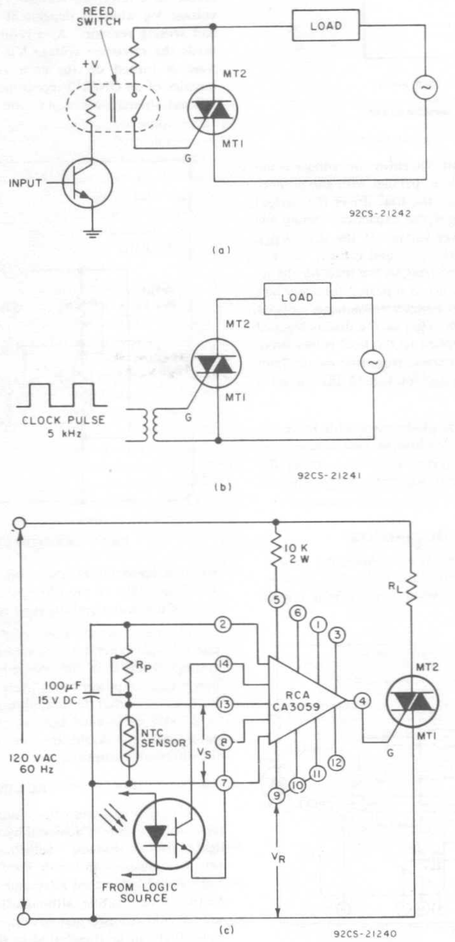

Fig.8 – (a) Isolation with reed relay; (b) isolation with pulse transformer; (c) isolation with light-activated devices.